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Advancing Shale Gas Recovery with Microwave Heating: A Study of Frequency, Time, and Thermal Effects in Reservoir Stimulation

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ABSTRACT - The advancement of unconventional hydrocarbon reservoirs, especially shale gas, has revolutionized energy production, offering a cleaner alternative to traditional fossil fuels. Despite its potential, shale gas extraction faces significant challenges due to the ultra-low permeability of formations, complex pore structures, and issues like water-blocking caused by hydraulic fracturing fluids. This study explores the innovative application of Microwave Heating (MWH) as a Formation Heat Treatment (FHT) technique to mitigate these challenges and enhance shale gas recovery. Microwave heating operates by converting electromagnetic energy into heat, leveraging the dielectric properties of reservoir materials to generate rapid, uniform, and volumetric heating. Numerical simulations were conducted to evaluate the effectiveness of MWH under varying frequencies (915 MHz, 2450 MHz, and 5800 MHz), focusing on temperature distribution, water volume reduction, and gas production. Results demonstrate that higher microwave frequencies, particularly 5800 MHz, lead to significant temperature increases, effective water vaporization, and permeability improvements. The 5800 MHz is the most effective for rapid and localized stimulation. The 2450 MHz provides a good balance of penetration and heating efficiency. Lastly, 915 MHz has limited utility, so its deeper penetration may find niche applications. This process facilitates gas desorption from the shale matrix, enhances diffusion, and improves cumulative gas recovery. The study highlights the environmental advantages of MWH, including reduced water usage and avoidance of groundwater contamination, positioning it as a sustainable alternative to traditional hydraulic fracturing. Furthermore, insights into shale reservoirs' thermal and electromagnetic properties are provided, offering guidance for optimizing MWH application in field conditions. This research underscores the potential of MWH to address critical operational challenges in unconventional reservoirs, paving the way for its integration into advanced shale gas recovery strategies.

Keywords: Microwave Heating (MWH), Formation Heat Treatment (FHT), reservoir stimulation, shale gas, unconventional reservoir.

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INTRODUCTION

Shale gas reservoirs are characterized by their ultra-low permeability matrix and a network of natural fractures enriched with minerals and organic deposits, particularly kerogen, the primary hydrocarbon source (Chapiro & Bruining 2015). These formations are challenging to exploit due to their limited ability to allow fluids to flow naturally (julikah et al. 2015; Musu et al. 2015). Experimental analysis of core samples from various reservoirs has shown that the average permeability of shale bedrock is extremely low, often measured in nano-darcies, with most pore sizes falling in the range of 4-200 nm (Guo et al. 2015). This microscopic pore structure restricts hydrocarbon mobility and recovery potential, necessitating advanced extraction techniques to overcome flow restrictions.

Shale gas production has been revolutionized by horizontal drilling and hydraulic fracturing technologies (Kartini 2014). Horizontal drilling enables operators to access extensive reservoir sections, maximizing contact with the gas-bearing zones. Hydraulic fracturing enhances production by creating fractures in the shale, increasing permeability, and enabling gas to flow to the wellbore (Boudet et al. 2014; Gallegos et al. 2015). However, hydraulic fracturing operations require significant amounts of water and additives, with a large portion of the injected fracture fluid remaining trapped in the formation. This retained water saturates the matrix, leading to water-blocking and a condition where water impedes the flow of gas through pore throats, further reducing permeability and production rates (Vidic et al. 2013; Wang et al. 2019).

The issues of water retention and formation damage underscore the need for alternative stimulation techniques. High-temperature treatments have shown promise in addressing water-blocking by vaporizing retained water and altering reservoir properties to improve gas flow (Cui et al. 2020; Xu et al. 2016).

Among these techniques, microwave heating (MWH) has emerged as a transformative, environmentally friendly solution. Unlike conventional hydraulic fracturing, which relies heavily on water, MWH is a waterless method that uses electromagnetic waves to generate heat. This heat rapidly increases the temperature of the reservoir, evaporating water and creating micro-cracks that enhance permeability (Chen et al. 2015).

Microwave fracturing is particularly advantageous in unconventional reservoirs because it targets specific areas with minimal environmental impact (Yang et al. 2017). The mechanism relies on the dielectric properties of the reservoir materials. Polar molecules such as water absorb microwave energy, leading to molecular rotation and friction, which generate heat. Additionally, minerals in the shale matrix act as microwave absorbers, enhancing the efficiency of the process. Beyond water evaporation, MWH accelerates the desorption and diffusion of methane molecules adsorbed on the shale matrix, significantly increasing gas recovery rates. This capability makes MWH an attractive alternative to traditional methods (Wang et al. 2015).

Microwave heating offers a compelling solution to address the limitations of conventional hydraulic fracturing (Chen et al. 2021). By combining its waterless, environmentally friendly nature with its ability to enhance desorption, permeability, and production rates, MWH has the potential to transform shale gas recovery. Further research and field trials will be essential to optimize its application and validate its efficacy in diverse reservoir conditions.

The state of the art

Microwave Heating (MWH) has emerged as an innovative technique to mitigate water-blocking and enhance gas recovery in tight gas sand and shale gas reservoirs (Wang et al. 2015). Laboratory studies have shown that MWH effectively reduces water saturation in the reservoir, simultaneously addressing issues of water blockage and improving permeability. The underlying mechanism involves heating water molecules and certain minerals in the formation using electromagnetic energy (Wang et al. 2016). This heating not only evaporates trapped water but also induces changes in the crystal structure of minerals, potentially enhancing the reservoir's permeability (Fianu et al. 2020). Experimental findings suggest that MWH is particularly effective in evaporating medium-salinity water, although high-salinity water requires a longer exposure time due to its lower microwave absorption efficiency.

In addition to water evaporation, MWH plays a crucial role in altering the physical and chemical properties of the reservoir. High-frequency electromagnetic waves generate localized thermal stresses that create micro-cracks in the rock matrix, further improving fluid mobility. These thermally induced fractures contribute to the evolution of matrix porosity and permeability, providing pathways for trapped hydrocarbons to flow more freely. The desorption of gas molecules often adsorbed on the surfaces of the rock matrix, is another significant benefit of MWH. By increasing the temperature of the reservoir, MWH accelerates gas desorption and enhances gas diffusion, facilitating higher recovery rates.

Numerical modelling studies, such as those using the Electro-Thermo-Hydro-Mechanical (EHTM) framework, have validated the effectiveness of MWH in improving gas recovery (Liu et al. 2018a). Simulations indicate that MWH can increase cumulative gas production by up to 44.9% over 31.7 years. This significant improvement is attributed to the dual effects of thermally induced fractures and enhanced gas desorption. Furthermore, the controlled application of MWH minimizes environmental impacts compared to traditional methods, such as hydraulic fracturing, which relies on large volumes of water and chemical additives.

Microwave heating-enhanced gas recovery (MWH-EGR) also has significant implications for unconventional reservoir development. MWH addresses key environmental concerns, such as groundwater contamination and excessive water usage, by reducing reliance on water-based stimulation techniques. Additionally, MWH offers flexibility in its application, as its efficiency depends on the dielectric properties of the reservoir, making it suitable for a wide range of geological formations. The ability to target specific areas within the reservoir with precision heating further enhances its appeal as a sustainable recovery technique.

MWH represents a paradigm shift in enhancing gas recovery in tight formations. Its ability to simultaneously address water-blocking, improve permeability, and boost gas production rates positions it as a transformative technology in the oil and gas industry. Continued advancements in modelling, field trials, and equipment design will be pivotal in optimizing MWH applications and unlocking their full potential in unconventional reservoirs.

Formation heat treatment

Formation Heat Treatment (FHT) is a pioneering matrix stimulation concept designed to address production challenges in unconventional reservoirs, particularly those caused by water-blocking and water phase trapping near the wellbore (Jamaluddin et al. 1995). These phenomena occur when residual water from hydraulic fracturing or natural formation water occupies pore spaces, significantly reducing gas permeability and flow rates. FHT aims to overcome these barriers by using thermal energy to evaporate trapped water, alter the rock matrix, and enhance reservoir properties. Laboratory studies have demonstrated that FHT effectively prevents formation damage caused by water retention, simultaneously increasing permeability and porosity.

In shale gas reservoirs, FHT has shown the ability to enhance matrix porosity and diffusivity at the micro-scale uniformly (Liu et al. 2018a). This uniform improvement enables more effective desorption of methane, which is often adsorbed onto the rock matrix. Methane desorption is critical in improving gas production rates, as the adsorbed phase can account for a significant portion of the recoverable gas in shale formations. By creating micro-fractures and enhancing pore connectivity, FHT facilitates the movement of desorbed gas to the wellbore, boosting production efficiency [15].

One of the most significant advantages of FHT is its ability to serve as a non-refractory hydraulic fracture assist technique. Unlike conventional methods that rely on excessive water and chemical additives, FHT reduces the need for additional water, minimizing environmental risks such as groundwater contamination and surface water depletion. It makes FHT particularly suitable for environmentally sensitive areas or regions facing water scarcity. Moreover, reducing water usage aligns with the industry's growing emphasis on sustainable practices and green technologies.

MWH has emerged as a key enabler of FHT. MWH converts electromagnetic energy into heat energy, offering a targeted and efficient heating solution for reservoir stimulation. High-frequency electromagnetic waves penetrate the reservoir, heating the rocks and fluids within their penetration depth. This heating mechanism is highly effective, as it does not rely on conduction or convection, enabling volumetric heating of the matrix. The dielectric properties of the reservoir materials, such as water, pyrite, and certain clay minerals, enhance the absorption of microwave energy, leading to rapid and uniform heating.

The ability of MWH to penetrate deep into the reservoir and generate localized heating is critical for the success of FHT. This method evaporates water trapped in pore spaces and induces thermal stresses that can create micro-fractures in the rock matrix. These microfractures increase permeability and facilitate gas migration (Wang et al. 2017). Furthermore, MWH's precision and efficiency allow for selective heating, reducing energy waste and minimizing unintended thermal impacts on surrounding formations.

FHT represents a paradigm shift in reservoir stimulation by integrating the principles of MWH into its framework. Its application in field settings has the potential to transform the economics of unconventional reservoir development, particularly in tight formations like shale gas reservoirs. By addressing key challenges such as water-blocking and formation damage while minimizing environmental impact, FHT, powered by MWH, offers a sustainable and efficient solution for enhancing hydrocarbon recovery. Future advancements in FHT technology, including enhanced modelling and optimization of microwave parameters, will further solidify its role as a cornerstone of next-generation reservoir stimulation.

Microwave heating

Microwaves are a form of electromagnetic wave characterized by a wavelength range of 1 mm to 1 m and a frequency spectrum between 300 MHz and 300 GHz. While microwaves are not inherently a source of heat, they can be converted into thermal energy through their interactions with materials that absorb, reflect, or transmit electromagnetic radiation (Bera & Babadagli 2015). This conversion is particularly effective in materials containing polar molecules, such as water or certain minerals, whose dielectric properties determine their ability to absorb microwave energy. In the context of shale reservoirs, microwave energy interacts with these polar molecules, causing rotational and vibrational motions that generate internal friction and result in rapid heating.

MWH is distinct from conventional heating methods, such as conduction or convection, as it enables volumetric heating. Unlike surface-dependent heat transfer, MWH heats materials internally, regardless of physical contact between the heating source and the target object (Bera & Babadagli 2015). This capability arises from the alignment and oscillation of molecular dipoles, such as those of water, under an alternating electric field created by microwave radiation (Vakhin et al. 2021). The rapid oscillation produces significant heat distributed uniformly across the material. It makes microwave heating highly efficient for applications where traditional methods are limited by slow heat propagation or physical barriers.

The transformation of electromagnetic energy into thermal energy occurs on a molecular level (Temizel & Aramco 2020). When exposed to MWH. In microwave radiation, materials with dielectric properties, such as water, pyrite, and coke, absorb the electromagnetic waves and convert them into heat (Zhu et al. 2021). This heating mechanism has several advantages, including energy efficiency, fast volumetric heating, and targeting specific zones within a material. Additionally, the heating rate in MWH is influenced solely by the dielectric properties of the material, enabling precise control over the process.

Such targeted heating is especially beneficial in enhancing the productivity of unconventional oil and gas reservoirs, where uneven heat distribution could adversely affect recovery.

One of the key advantages of microwave heating is its ability to achieve almost instantaneous heating. Unlike thermal energy, which is eight orders of magnitude higher in intensity, microwave field energy can accelerate reactions hundreds of times under the right conditions. It has significant implications for hydrocarbon recovery, as it facilitates the decomposition of high molecular weight hydrocarbons, improving the quality and yield of extracted products. Furthermore, MWH induces molecular fragmentation, promoting the breakdown of chemical bonds in complex hydrocarbons and enhancing the overall recovery process. In practical applications, MWH leverages down-hole transmitting antennas to deliver high-frequency electromagnetic waves deep into the reservoir. Geological variations less influence this technology and can uniformly distribute heat over larger reservoir volumes (Bientinesi et al. 2013). Advances in mathematical modelling and numerical simulations have improved the prediction and visualization of heating patterns, allowing for optimized application in the field (Asghari & Sheidaei 2011). Recent developments in coupled electromagnetic-thermal modelling have enabled a better understanding of MWH's effects on reservoir materials. However, much research has focused on non-petroleum sectors such as food, wood, and minerals (Liu et al. 2018b).

Comparisons between MWH and conventional heating methods reveal significant advantages for microwave technology. These include faster heating rates, more uniform temperature distribution, and enhanced quality of recovered hydrocarbons. For instance, in shale oil recovery, MWH has been shown to improve oil quality and gas production by facilitating significant molecular fragmentation and accelerating the decomposition of chemical bonds. This unique mechanism of action makes MWH a transformative tool in the oil and gas industry, particularly in enhancing the recovery of hydrocarbons from complex and unconventional reservoirs.

In conclusion, MWH represents a groundbreaking advancement in energy transfer technologies, offering a sustainable and efficient alternative to traditional heating methods (Zhu et al. 2019). Its ability to rapidly and uniformly heat materials, environmental benefits, and operational efficiency underscore its potential as a cornerstone technology in unconventional resource development. Future advancements in equipment design and modelling techniques will further enhance its applicability, ensuring its integration into mainstream oil and gas operations.

METHODOLOGY

Simulation modelling plays a critical role in understanding reservoir conditions and evaluating the effects of various stimulation techniques on reservoir performance. In this study, numerical simulations were employed to analyze temperature distribution and its impact on shale gas reservoirs using commercial software (Comsol Multiphysics 5.6). The simulated reservoir comprises a type of shale rock that has been hydraulically fractured, resulting in increased water saturation. This retained water obstructs permeability, creating a challenging gas flow and production scenario. By integrating the concept of FHT through MWH, the study seeks to evaluate the potential of converting electromagnetic energy into heat energy to mitigate these challenges. The reservoir properties and electrical components used in the simulation are detailed in Tables 1 and 2, which include parameters such as permeability, porosity, initial temperature, depth, and pressure. Notably, the reservoir permeability is exceptionally low, reflecting the characteristic ultra-tight nature of shale formations. At the same time, the thermal and electrical properties provide a basis for assessing the heating efficiency and energy transfer during microwave application.

Geometric modelling was conducted in three dimensions (3D) to accurately represent the reservoir's length, width, and height. The approach ensures a realistic depiction of the reservoir's spatial characteristics, enabling precise heat distribution and fluid dynamics simulation. Following the geometric modelling, materials were assigned electrical and thermal properties as listed in Table 2, such as thermal conductivity, relative permittivity, and electrical conductivity. These parameters are crucial in defining the interaction between microwaves and the reservoir rock, as they determine the efficiency of heat penetration and distribution.

MWH scenarios were created for a range of frequencies, specifically 915 MHz, 2450 MHz, and 5800 MHz, over a simulated period of 360 days (Fianu et al. 2020). Each frequency was selected to explore its unique impact on heat transfer, water evaporation, and subsequent changes in reservoir properties. Hypothetically, higher frequencies typically offer deeper penetration and higher heating rates, making them particularly suitable for volumetric heating in tight formations. One of the key outputs of the simulation was the analysis of volume changes during heating. The relationship between fluid volume and temperature was calculated using Jacques Charles' Law, which establishes that the volume of a gas (or fluid under certain conditions) is directly proportional to its absolute temperature when pressure remains constant. The equation for the relationship between fluid volume and temperature at constant pressure was developed in 1823. The equation used is as follows:

Where:

$$\left(\frac{V_1}{T_1}\right)^n = \left(\frac{V_2}{T_2}\right)^n \quad (1)$$

V_1 is the initial fluid volume water in the reservoir (m^3), T_1 is the initial fluid temperature water in the reservoir, V_2 is the fluid volume water after heating (m^3), and T_1 is the fluid temperature water after heating.

This relationship allows for precise quantification of the thermal effects on fluid expansion or contraction, providing insights into the efficiency of MWH in reducing water retention and improving gas flow. The results of this simulation are expected to demonstrate the advantages of MWH in increasing reservoir permeability and enhancing gas production, particularly by addressing water-blocking and facilitating methane desorption from the shale matrix. The combination of advanced modelling techniques and tailored simulation scenarios highlights the importance of integrating high-frequency microwave energy into reservoir management. This approach optimizes thermal stimulation and underscores its potential as a sustainable and efficient alternative to conventional hydraulic fracturing methods. Further validation through field trials and enhanced modelling will pave the way for the broader adoption of MWH in unconventional reservoir development.

Table 1. Reservoir properties.

Component	Value
Permeability (mD)	7.5×10^{-5}
Porosity	0.05
Initial Temperature (K)	350
Depth (ft)	5463
Initial Pressure (Psia)	1508

Table 2. Electrical component

Component	Value
Thermal Conductivity (J/(m.day.˚C))	1.73×10^5
Thermal Gradient (˚C/m)	2.8/100
Heat Capacity (J/(cm^3˚C))	2.385
Microwave Frequency (GHz)	2.45
Operation Power (Watt)	1000
Relative Permittivity	5
Relative Permeability	0.999985
Electrical Conductivity	0.02

Source: (Kamari et al. 2018; Wang et al. 2017)

RESULT AND DISCUSSION

Results of heating frequency analysis

The study focuses on the frequencies selected for MWH, ranging from 300 MHz to 300 GHz, a spectrum that includes various frequencies known for their heating efficiency in industrial and research applications. Specifically, the chosen frequencies of 915 MHz, 2450 MHz, and 5800 MHz have been widely explored in previous studies due to their effective interaction with dielectric materials and suitability for energy transfer in subsurface formations. These frequencies offer a balance between penetration depth and heating efficiency, which is crucial for achieving the desired stimulation effects in tight shale gas reservoirs. The figures show the electrical field distribution for various frequencies (915 MHz, 2450 MHz, and 5800 MHz). They visualize the intensity and distribution of the electric field within the system modelled in units of Volts per meter (V/m).

Lower frequencies (915 MHz) offer deeper penetration but reduced intensity, making them suitable for bulk heating. Higher frequencies (2450 MHz and 5800 MHz) concentrate energy closer to the surface, resulting in more localized heating, which may be advantageous for specific applications requiring surface treatment. The 2450 MHz frequency balances penetration depth and heating efficiency, making it a preferred choice in microwave applications like food processing and medical treatments. The field becomes less uniform at higher frequencies, as in 5800 MHz. It could lead to uneven heating unless controlled. At 5800 MHz, the penetration depth is significantly reduced compared to lower frequencies.

Use 5800 MHz for applicationts requiring localized heating, such as wellbore cleaning, paraffin removal, or heating specific high-viscosity zones near the injection or production wells.

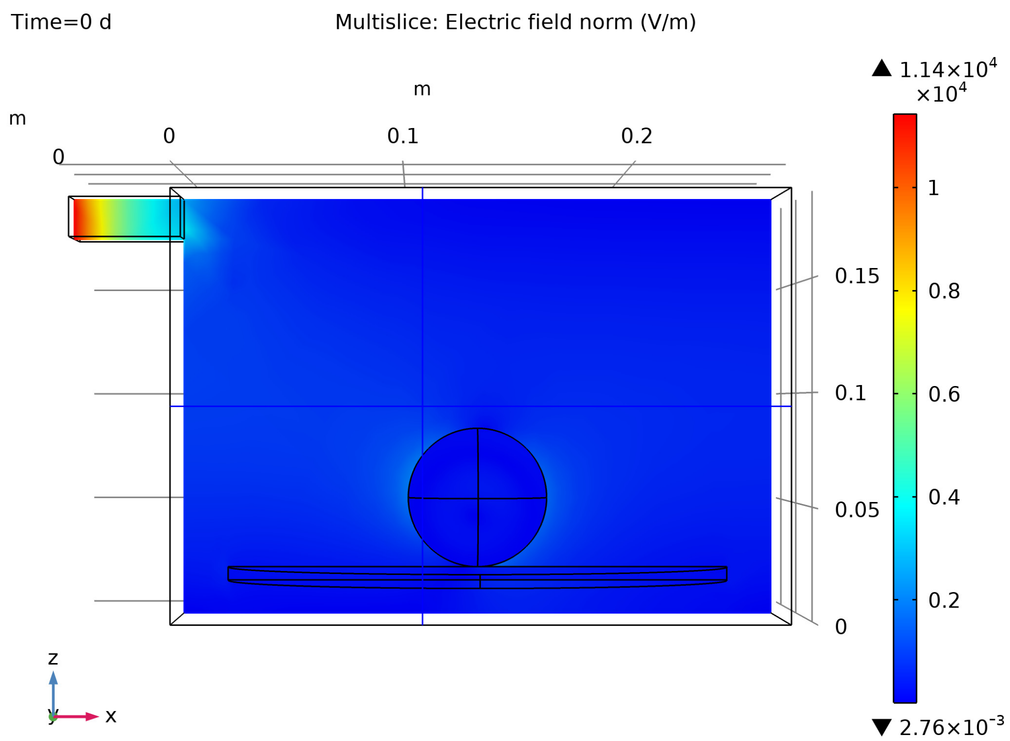

Figure 1. Electrical region at freq. 915 MHz

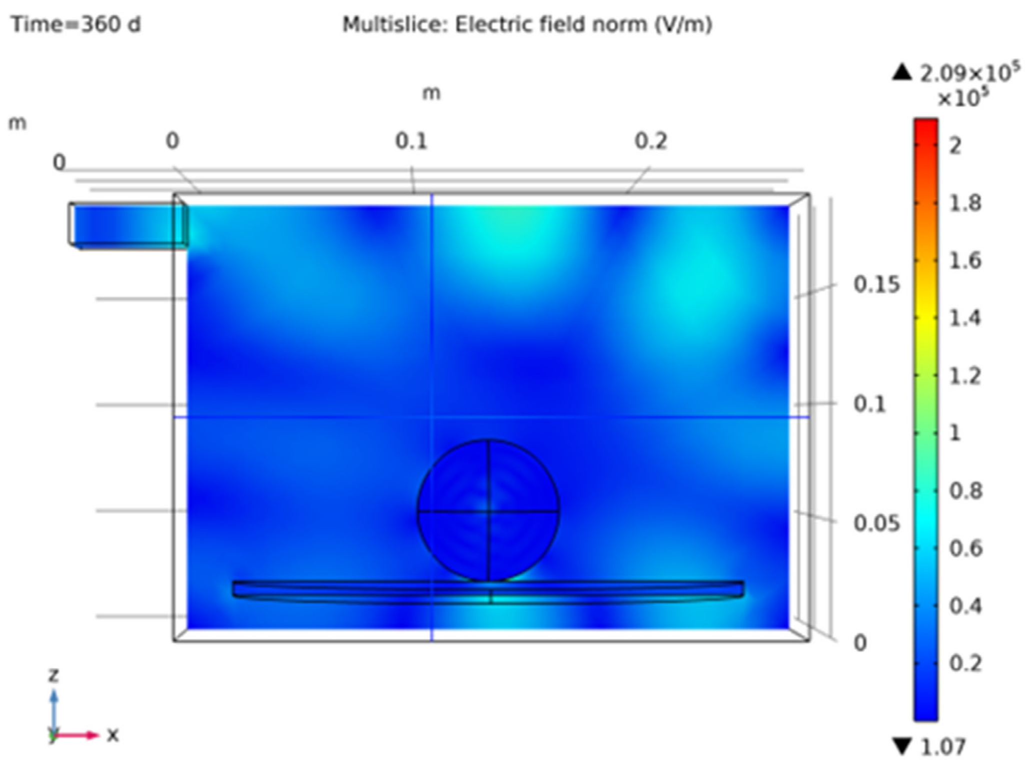

Figure 2. Electrical region at freq. 2450 MHz

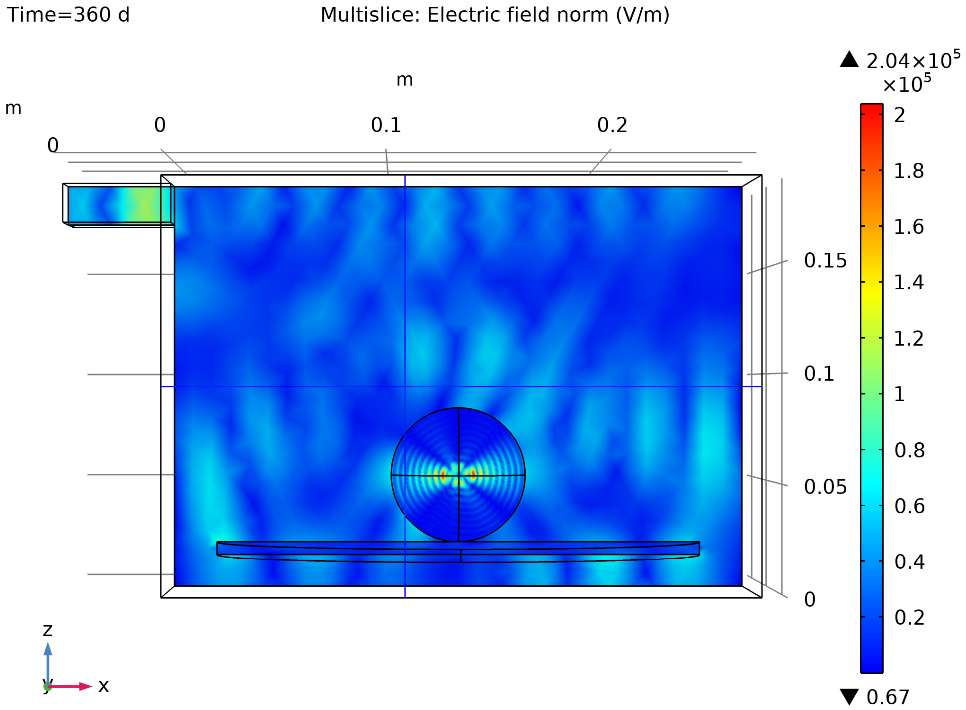

Figure 3. Electrical region at freq. 5800 MHz.

The choice of these specific frequencies aligns with industry standards and past research results that have identified them as optimal for heating water-saturated and mineral-rich formations. The frequencies target different aspects of the shale matrix: lower frequencies, like 915 MHz, have deeper penetration but may provide less intense heating, while higher frequencies, like 5800 MHz, generate more concentrated heat but may have limited depth of influence. The study aims to identify the most effective frequency for maximizing temperature distribution and enhancing gas recovery by evaluating a range of frequencies.

The study also incorporates time-dependent scenarios, with heating durations ranging from 0 to 360 days, a timeline that reflects the long-term nature of reservoir stimulation processes. This extended timeframe allows for a comprehensive assessment of how prolonged exposure to microwave energy impacts the temperature distribution within the reservoir. It also provides insights into the cumulative effects of MWH on water evaporation, gas desorption, and rock fracturing, which are essential for improving permeability and sustaining production rates in shale gas reservoirs. After running simulations across these frequency and time-dependent scenarios, the next step in the analysis involves examining the relationship between heating time and temperature increase. This relationship is critical for understanding the effectiveness of MWH at different intervals and identifying the frequency and time combinations that yield the highest temperature gains. In Figure 1, the 3D temperature distribution results visually represent how temperature spreads throughout the reservoir over time, highlighting the differences in heating patterns at each frequency.

By analyzing these 3D temperature distributions, the study seeks to conclude the optimal heating frequency and duration for achieving uniform and effective heating in the reservoir. These findings are expected to offer valuable guidance for field applications of MWH, where maximizing temperature increase while minimizing energy consumption and environmental impact are key objectives.

The temperature results in Figure 4 illustrate the potential of MWH as a transformative approach for enhancing gas production in unconventional reservoirs, with each frequency contributing unique advantages to the heating process.

The three cases (915 MHz, 2450 MHz, and 5800 MHz frequencies) demonstrate different heating efficiencies, temperature distributions, and potential applications in shale gas reservoirs. Below is a detailed comparison of their performance:

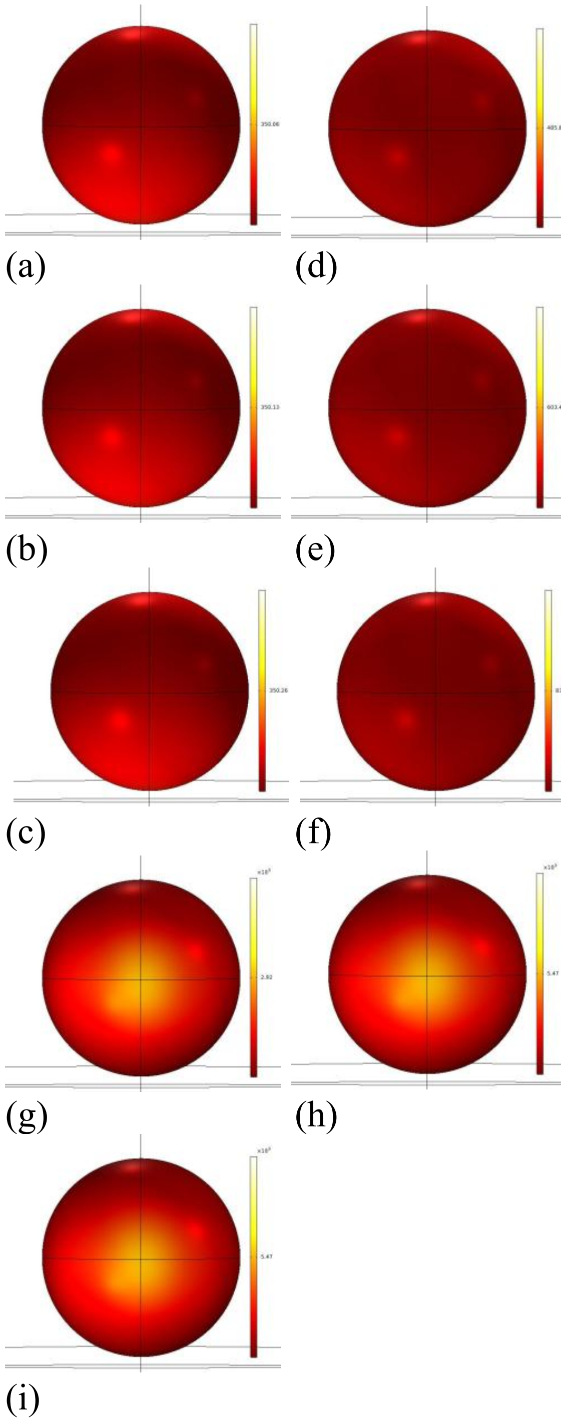

Figure 4. (a) Day 90, (b) Day 180 and (c) Day 360 using 915 MHz frequency, (d) Day 90, (e) Day 180 and (f) Day 360 using 2450 MHz frequency, (g) Day 90, (h) Day 180 and (i) Day 360 using 5800 MHz frequency.

Results of temperature analysis

Figure 2 illustrates the temperature progression over 360 days in a shale gas reservoir subjected to microwave heating at a frequency of 915 MHz. The x-axis represents the heating duration in days, while the y-axis shows the temperature in Kelvin. The curve exhibits a gradual initial rise in temperature, followed by an accelerating increase as time progresses, indicating an exponential trend.

The graph starts with a relatively flat curve, where temperature shows a minimal increase from its baseline of 350 K. This slow response in the early days suggests that at a frequency of 915 MHz, the microwave energy is not immediately effective in generating significant heat within the reservoir. In this phase, the microwave energy primarily goes into overcoming the thermal inertia of the rock matrix and fluids. Since 915 MHz is a lower frequency than alternatives like 2450 MHz and 5800 MHz, it has less direct impact on heating polar molecules in the reservoir, such as water, which have a lower absorption efficiency at this frequency. Beyond approximately 200 days, the temperature rises sharply, indicating an exponential increase. This phase likely corresponds to where the reservoir materials have absorbed enough energy for a more noticeable thermal response. In this phase, the accumulated heat may cause minor structural changes within the reservoir, such as microfracture and gradual desorption of gas molecules. However, due to the relatively low heating effect of the 915

Table 3. Comparative analysis of microwave heating frequencies

Parameter	915 MHz	2450 MHz	5800 MHz
Max Temperature (K)	~350.22	~540	~6500
Heating Rate	Slow	Moderate	Rapid
Water Vaporization	Minimal	Effective (gradual)	Complete (rapid)
Gas Desorption	Limited	Moderate	High
Permeability Improvement	Minimal	Moderate	Significant
Energy Requirements	Low	Moderate	High
Operational Complexity	Low	Moderate	High

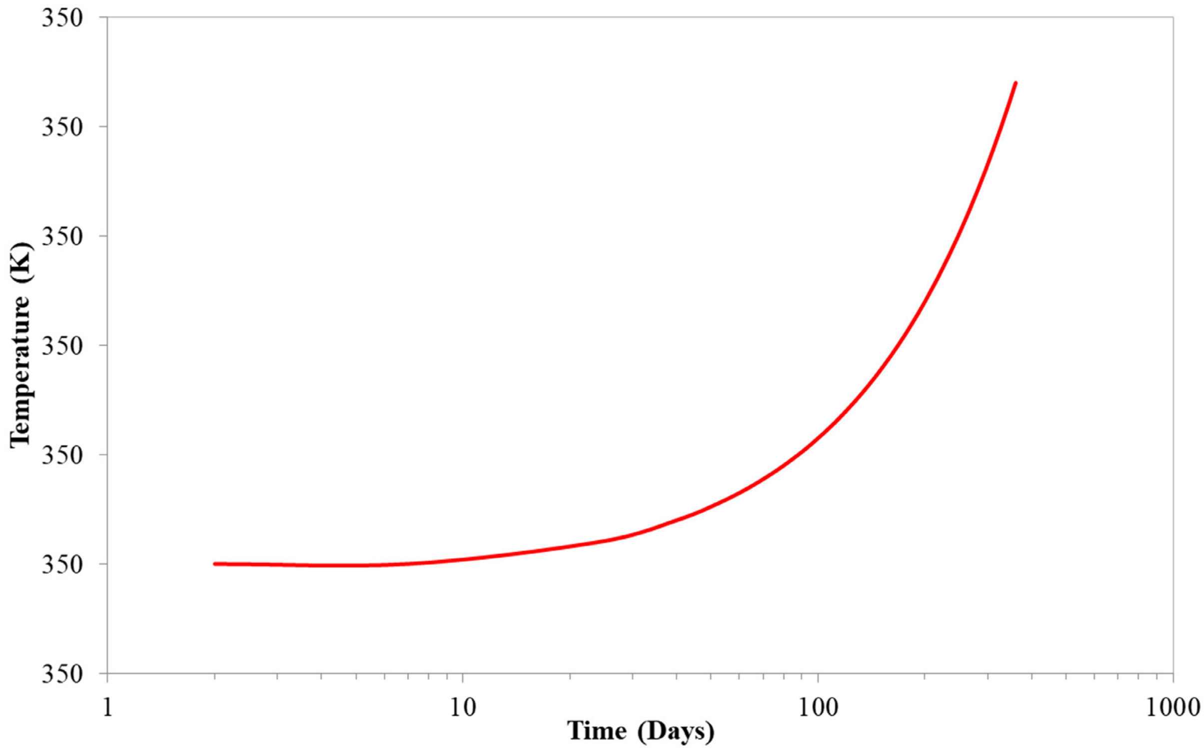

Figure 5. Temperature for 0-360 days using 915 MHz frequency

MHz frequency, these changes are less pronounced than with higher frequencies.

The slow initial response and gradual temperature increase observed in this graph suggest that 915 MHz may not be optimal for efficient heating in shale gas reservoirs. While it can penetrate the reservoir deeply, its lower heating effect limits its ability to generate the rapid and substantial temperature rise necessary for effective water evaporation and gas desorption. Also, its slow effect avoids structural damage to sensitive formations. The slow temperature buildup with 915 MHz implies that longer heating durations or higher power inputs may be required to achieve meaningful thermal effects. It increases operational costs and energy requirements, making this frequency less cost-effective than higher frequencies that achieve faster heating within shorter timeframes.

In summary, the temperature vs. time graph for 915 MHz illustrates a relatively slow and gradual heating trend, suggesting that this frequency may not be optimal for rapid or intense stimulation of shale gas reservoirs. While it eventually achieves some temperature increase, its lower energy absorption efficiency limits the effectiveness of 915 MHz. For optimal results in shale gas applications, especially where overcoming water-blocking and enhancing permeability are key, higher frequencies would likely provide better outcomes.

The curve begins with a modest temperature rise, starting around 360 K (near the baseline of the reservoir's initial temperature). It indicates that, in the early stages, microwave energy is primarily absorbed by the reservoir's water and minerals, which have dielectric properties.

Compared to the 915 MHz frequency, the 2450 MHz frequency shows more effective energy absorption, as evidenced by the steeper initial rise in temperature. It is due to the higher interaction efficiency of 2450 MHz with polar molecules like water, making it more effective in generating heat. The higher frequency (2450 MHz) allows for better penetration into the shale matrix and more efficient energy transfer. This phase is crucial for enhancing reservoir permeability by promoting gas desorption and creating micro-fractures due to thermal expansion. By this stage, the energy absorbed by the

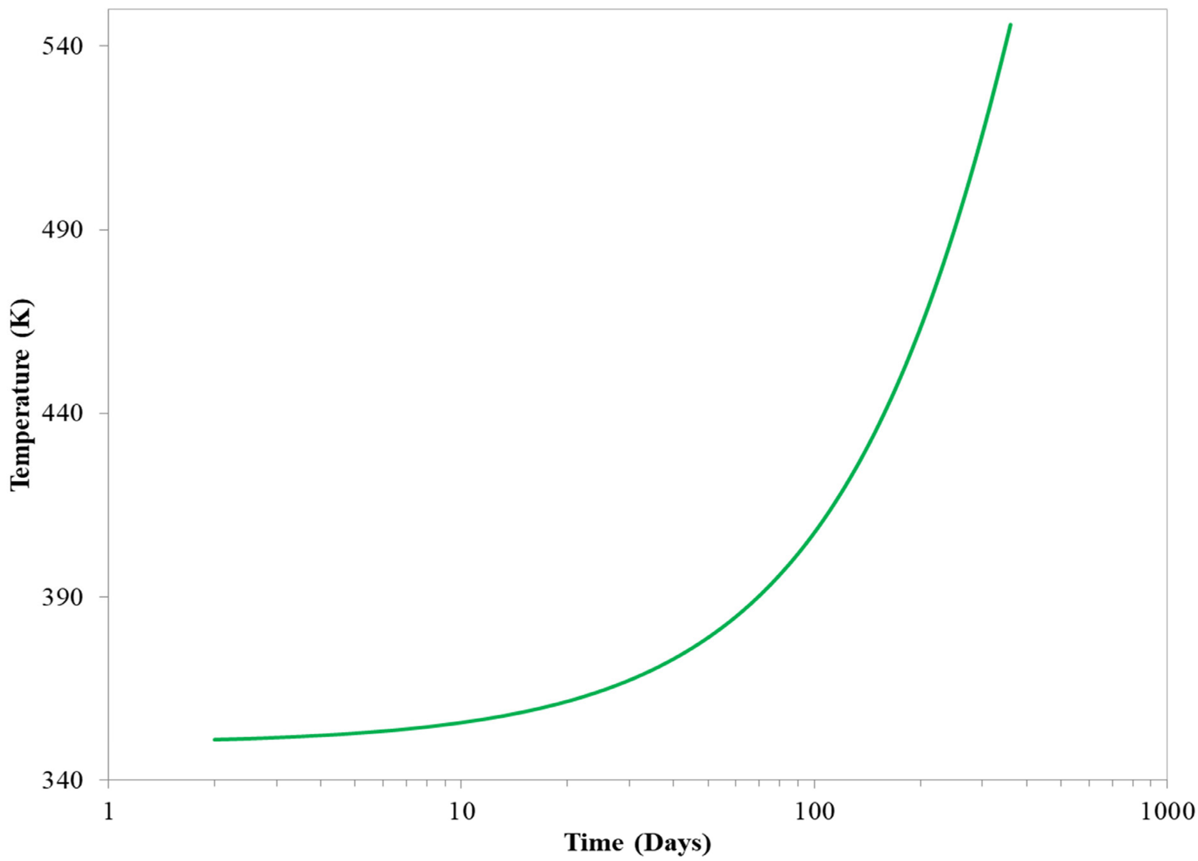

Figure 6. Temperature for 0-360 days using 2450 MHz frequency

reservoir begins to vaporize retained water and heat surrounding rock materials more effectively.

After approximately 200 days, the graph shows a dramatic exponential rise in temperature, reaching over 540 K by day 360. This rapid heating indicates that the reservoir has reached a point where absorbed energy overcomes thermal inertia and significantly alters reservoir conditions. At this stage, water trapped in pore spaces is likely to be completely vaporized, and the thermal stresses may cause significant structural changes in the rock, such as the formation of new fractures and increased pore connectivity. These effects are critical for improving gas flow and production rates.

The graph indicates that 2450 MHz is highly effective in heating the reservoir to temperatures sufficient for vaporizing retained water. It directly addresses water-blocking issues that commonly hinder gas flow in tight shale formations. The gradual but substantial increase in temperature over time suggests that the 2450 MHz frequency enhances permeability by altering the physical structure of the shale. The thermal expansion caused by heating can create microfractures, allowing for easier gas migration toward the wellbore. As the temperature exceeds 400 K, methane and other hydrocarbons adsorbed on the shale matrix begin to desorb, leading to increased gas recovery rates. The sharp rise in temperature beyond 200 days highlights the potential of this frequency to accelerate gas production over time. Compared to lower frequencies (e.g., 915 MHz), 2450 MHz provides a better balance between penetration depth and heating efficiency. While higher frequencies like 5800 MHz may offer even more rapid heating, 2450 MHz achieves sufficient heating at depths typical of most shale reservoirs without excessive energy requirements.

The temperature profile at 2450 MHz demonstrates the frequency's suitability for microwave heating applications in shale gas reservoirs. It provides a clear advantage in terms of efficient water evaporation, gas desorption, and permeability enhancement. This frequency is beneficial for achieving sustained thermal effects over a prolonged period (360 days), making it a promising candidate for applications requiring balanced heating performance. By promoting desorption and reducing water retention, 2450 MHz can significantly improve gas recovery rates while maintaining operational and energy efficiency.

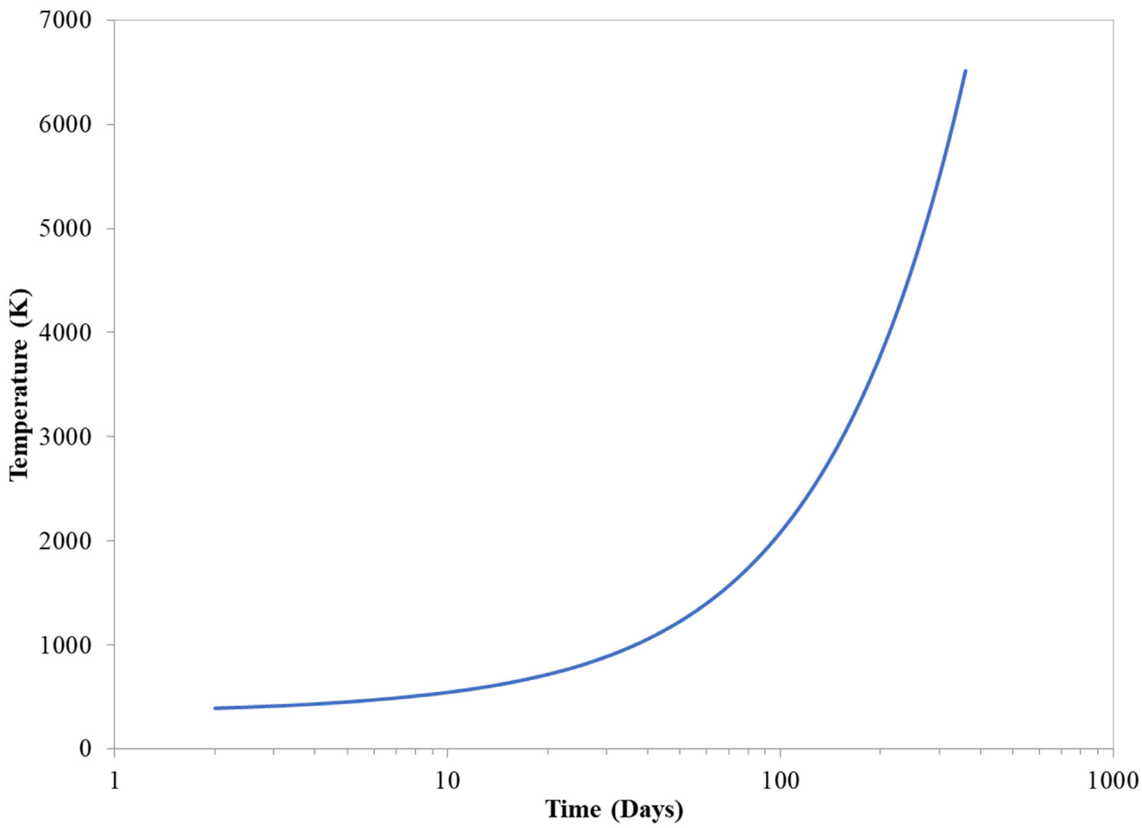

Figure 7. Temperature for 0-360 days using 5800 MHz frequency

The temperature rise begins moderately, increasing gradually from the baseline. The response is more pronounced compared to lower frequencies (e.g., 915 MHz and 2450 MHz) due to the higher energy absorption capability of the reservoir materials at 5800 MHz.

This initial phase reflects the buildup of thermal energy as microwave radiation interacts with polar molecules like water and minerals with high dielectric properties. The energy transfer is highly efficient at this frequency, leading to a faster temperature response even during the early stages. It is due to the high potential of water in microwave absorption, and thus, these waves are first absorbed by free or bound water molecules in the gas shale and cause the material to heat up (Taheri-Shakib & Kantzas 2021).

Table 4. Simulation results at 90 days, 180 days and 360 days.

Time (d)	915 MHz	2450 MHz	5800 MHz
90	350.06 °K	401.83 °K	1910.7 °K
180	350.11 °K	452.28 °K	3445.5 °K
360	350.22 °K	545.87 °K	6515.2 °K

Higher frequencies result in significantly higher temperature profiles due to their ability to interact efficiently with polar molecules, such as water. It is critical for overcoming water-blocking and promoting gas desorption in tight shale formations.

Results of volume change analysis

The 915 MHz has a minimal reduction in water volume, indicating that this frequency is ineffective at vaporizing retained water. The slow heating process limits its ability to address water-blocking within the reservoir. The 2450 MHz produces a noticeable reduction in water volume over time, reflecting the frequency's moderate heating efficiency. While effective, it requires longer durations to achieve significant results compared to 5800 MHz. The 5800 MHz shows a dramatic reduction in water volume, with the remaining water reduced to just 7029.76 m^3 at 360 days. The rapid and intense heating facilitates complete water vaporization, effectively eliminating water-blocking. The frequency of 5800 MHz is the most effective at reducing water volume due to its high energy absorption rate, which accelerates water vaporization. It directly improves reservoir permeability and enhances gas flow.

Table 5. Simulation results at 90 days, 180 days and 360 days.

Time (d)	915 MHz Volume (m^3)	2450 MHz Volume (m^3)	5800 MHz Volume
90	130835.57	113979.29	23970.43
180	130816.89	101265.37	13292.79
360	130775.80	83903.31	7029.76

Mechanisms driving frequency performance

The lower frequency (915 MHz) results in deeper penetration but poor energy absorption by the shale matrix. Its inefficiency in heating water molecules makes it unsuitable for rapid or high-impact applications. It is best suited for low-intensity and long-term heating applications in less complex reservoirs where depth penetration is prioritized over heating intensity. The 2450 MHz provides a good balance of penetration and heating efficiency. Its ability to moderately heat the matrix and vaporize water over time makes it practical for medium-scale reservoir stimulation. The applications are suitable for reservoirs with moderate challenges, where slow but steady permeability improvements and gas desorption are acceptable. The high-frequency waves (5800 MHz) interact strongly with water and minerals (e.g., pyrite, marcasite) in the shale, producing rapid heating. It facilitates water vaporization, thermal fracturing, and pore structure modification, resulting in significant permeability and diffusivity improvements. The 5800 MHz is ideal for tight, shallow reservoirs requiring intense and localized stimulation. Its rapid results make it the preferred choice for addressing severe water-blocking and low gas mobility.

Pore structure and permeability improvements

At higher frequencies, such as 5800 MHz, microwave heating modifies the pore structure by reducing absorption pores and increasing diffusion and seepage pores (Fu et al. 2021). It leads to enhanced gas desorption due to increased temperature. It improved connectivity within the shale matrix as fractures formed along and perpendicular to the bedding planes. It also increased permeability parallel to the bedding direction, facilitating hydrocarbon flow to the wellbore (29). The structural changes induced by higher-frequency MWH (5800 MHz) make it a transformative technology for tight gas formations, overcoming the inherent challenges of ultra-low permeability.

Deep and powerful correlation from the three cases

The three cases 915 MHz, 2450 MHz, and 5800 MHz reveal critical insights into the interplay between microwave frequency, heating efficiency, and its impact on reservoir properties such as permeability, gas desorption, and water vaporization. Here are the key correlations we can draw, along with their implications.

Frequency-dependent energy absorption

Higher frequencies (5800 MHz) result in more efficient energy absorption by the dielectric materials in the reservoir, such as water and certain minerals, compared to lower frequencies (915 MHz and 2450 MHz). It is due to the stronger interaction of higher-frequency microwaves with polar molecules. The ability of higher frequencies to generate rapid and intense heating makes them ideal for scenarios where quick water vaporization and gas desorption are critical. However, their penetration depth decreases, indicating that high-frequency MWH is best suited for localized heating in reservoirs with tight, shallow zones.

Cumulative energy transfer vs. Time

The cumulative heating effect increases exponentially with higher frequencies as time progresses. While 915 MHz shows slow linear growth in temperature, 2450 MHz achieves moderate growth, and 5800 MHz exhibits an exponential temperature surge after 200 days. The exponential relationship suggests that higher frequencies not only accelerate the heating process but also enhance reservoir permeability and gas flow significantly within shorter durations. It underscores the importance of balancing frequency selection with heating duration to optimize energy usage and minimize operational costs.

Water vaporization and permeability enhancement

The efficiency of water vaporization directly correlates with the frequency. At 915 MHz, minimal water vaporization occurs, leaving water-blocking issues unresolved. At 2450 MHz, water vaporizes gradually, improving permeability over time. At 5800 MHz, water is vaporized rapidly and completely, leading to immediate and significant permeability improvement. It highlights the transformational role of higher-frequency MWH (5800 MHz) in addressing water-blocking, particularly in tight shale reservoirs. The complete removal of retained water facilitates gas flow and makes higher frequencies essential for maximizing hydrocarbon recovery in water-sensitive formations.

Thermal effects and gas desorption

Higher temperatures achieved by 5800 MHz induce more significant thermal stress on the shale matrix, creating micro-fractures that significantly enhance gas desorption and flow. At lower frequencies (915 MHz), the lack of sufficient thermal energy limits these effects, while 2450 MHz achieves moderate improvements. Gas desorption is strongly temperature-dependent, and higher frequencies are crucial for liberating adsorbed hydrocarbons in ultra-tight formations. This correlation indicates that selecting the right frequency is vital for unlocking maximum gas recovery potential, especially in low-permeability zones.

Trade-off between penetration depth and heating intensity

Lower frequencies (915 MHz) penetrate deeper into the reservoir but generate less heat, while higher frequencies (5800 MHz) produce intense, localized heating with limited penetration depth. This trade-off emphasizes the need to tailor frequency selection based on reservoir characteristics: (a) lower frequencies may be more appropriate, albeit less efficient, in heating for deeper formations. (b) Higher frequencies like 5800 MHz are ideal for rapid stimulation and production enhancement for shallow, tight reservoirs.

Sustainability and environmental considerations

Due to their efficiency in vaporizing water and enhancing gas desorption, higher frequencies reduce reliance on water-intensive hydraulic fracturing and chemical additives. It makes MWH a more sustainable alternative for reservoir stimulation. The environmental advantages of higher frequencies align with industry trends toward reducing water usage and minimizing ecological impact. This correlation positions MWH, especially at 5800 MHz, as a green technology for future reservoir management.

Strategic insights for application

The 915 MHz offers deep penetration but lacks sufficient heating intensity. Best for long-duration, low-intensity applications where minimal heating is acceptable (e.g., low-impact stimulation or thermal conditioning over large reservoir areas). The 2450 MHz has balanced penetration depth and heating efficiency, making it suitable for reservoirs requiring moderate stimulation. It can address water-blocking and permeability issues over time, though not as rapidly as 5800 MHz. The 5800 MHz has the most transformative frequency, achieving rapid and intense heating. It is best suited for challenging tight shale formations where water-blocking and gas desorption are critical issues. However, its operational complexity and higher energy demands must be carefully managed.

The robust correlation lies in the interplay of frequency, temperature, and time, which directly governs the success of microwave heating in shale gas recovery. Higher frequencies deliver exponentially greater thermal energy, enabling rapid water removal, permeability enhancement, and gas desorption. However, their effectiveness diminishes with depth due to reduced penetration. Hence, the choice of frequency must therefore balance: 1).Reservoir Depth: Lower frequencies for deeper penetration; higher frequencies for shallow, localized zones; 2). Operational Goals: Gradual heating with 2450 MHz for long-term stimulation; rapid, intense stimulation with 5800 MHz for immediate results; 3). Energy and Sustainability: Higher frequencies like 5800 MHz are most effective for reducing water reliance and promoting environmentally friendly recovery.

CONCLUSION

Microwave heating represents a groundbreaking advancement in reservoir stimulation technology, offering unparalleled potential to enhance gas recovery from shale formations. By efficiently removing water-blocking, improving permeability, and accelerating gas desorption, MWH addresses the fundamental challenges of unconventional reservoir development. Among the frequencies analyzed, 5800 MHz is the most effective for rapid and localized stimulation. It addresses water-blocking, enhancing permeability, and desorbing gas in tight formations. However, its higher operational complexity and energy requirements make it more suitable for severe reservoir conditions where quick and high-impact results are needed. Meanwhile, 2450 MHz provides a balanced approach for moderate applications and strikes a good balance between penetration depth and heating efficiency. It is ideal for gradual reservoir stimulation, moderately improving permeability and gas desorption. Although 915 MHz has limited utility, its deeper penetration may find niche applications. It is best for applications where slow, minimal heating over long periods is acceptable. By understanding these correlations, the users can optimize MWH applications to achieve maximum hydrocarbon recovery, minimal environmental impact, and cost-effective operations tailored to specific reservoir conditions.

The study's broader implications extend beyond operational efficiency to include sustainability and environmental stewardship. MWH aligns with the global push toward greener energy production by minimizing water usage and reducing the ecological impact of traditional hydraulic fracturing. With continued advancements in energy efficiency, modelling, and field validation, MWH has the potential to become a cornerstone technology in the future of shale gas production. The study underscores the transformative role of frequency-optimized microwave heating in unlocking the true potential of shale gas reservoirs, marking a critical step toward sustainable and efficient energy production in a rapidly evolving industry.

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GLOSSARY OF TERMS

Symbols	Definition	Unit
MWH	Microwave Heating	
FMH	Formation Heat Treatment	
MWH-EGR	Microwave heating-enhanced gas recovery	
EHTM	Electro-Thermo-Hydro-Mechanical	

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